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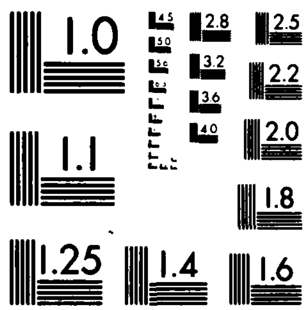

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ANALYSIS OF LUNAR LASER RANGING DATA AND PERFORMANCE AND ANALYSIS OF VLBI OBSERVATIONS FOR GEODETIC PURPOSES

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1 October 1980 - 30 September 1981

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20. Lunar laser ranging (LLR) observations made by the McDonald Observatory from 1970 through 1980 have been analyzed to estimate the variation of latitude and Universal Time (UT). We have compared these estimates with determinations of earth rotation from other techniques. For observations obtained in two one-week periods in September and October 1980, during the International "MERIT" (Measurement of Earth Rotation and Intercomparison of Techniques) Short Campaign, the root-mean-square difference between LLR and VLBI determinations of UT was 0.3 milliseconds. We have also used LLR determinations of UT to derive changes in length-of-day (lod) and compared these with changes in lod inferred from changes in the polar component of the earth's atmospheric angular momentum. A common, persistent ~50-day fluctuation was identified in these lod values.

Four sessions of observations involving radio telescopes in the United States and Europe have been carried out using the Mark III very-long-baseline-interferometry (VLBI) system: November 1979, July 1980, September 1980, and October 1980. These observations have been analyzed to estimate distances from radio telescopes in the U.S. to three Europea[illegible]s (Onsala, Sweden; Effelsberg, F. R. Germany; and Chilbolton, E[illegible]gland). The data from the September and October sessions were also analyzed to yield estimates of the solid-earth tide parameters, h and ℓ, and the tidal lag angle. During the July 1980 session, special observations were made to determine the precision of the corrections for the propagation delay in the ionosphere.

ABSTRACT

Lunar laser ranging (LLR) observations made by the McDonald Observatory from 1970 through 1980 have been analyzed to estimate the variation of latitude and Universal Time (UT). We have compared these estimates with determinations of earth rotation from other techniques. For observations obtained in two one-week periods in September and October 1980, during the International "MERIT" (Measurement of Earth Rotation and Intercomparison of Techniques) Short Campaign, the root-mean-square difference between LLR and VLBI determinations of UT was 0.3 milliseconds. We have also used LLR determinations of UT to derive changes in length-of-day (lod) and compared these with changes in lod inferred from changes in the polar component of the earth's atmospheric angular momentum. A common, persistent ~50-day fluctuation was identified in these lod values.

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I. ANALYSIS OF LUNAR LASAR RANGING OBSERVATIONS

A. Determination of Earth Rotation Parameters

We have analyzed lunar laser ranging (LLR) observations from the McDonald Observatory to estimate the variation of latitude and Universal Time (UT) for the period 1970 through 1980. The typical formal uncertainties of our values are about 5 milliarc-seconds and 0.5 milliseconds of time, respectively. We have compared our values of variation of latitude with those derived from pole positions determined using classical astrometric, satellite Doppler, and satellite laser ranging techniques for the period July 1976 to November 1978 when data from all of these techniques were available. A description of our analysis and the results of these intercomparisons are given in Langley _et al._ [1982a]. Our estimates were also submitted to the Bureau International de l'Heure (BIH) and have been published in its _Annual Report for 1980_ [Langley _et al._, 1981].

For the two one-week periods during the International MERIT (Measurement of Earth Rotation and Intercomparison of Techniques) Short Campaign that VLBI data were obtained, we have compared our smoothed LLR UT values with (unsmoothed) ones obtained from the VLBI observations discussed in Section II.A. The root-mean-square (rms) difference about the mean difference is 0.3 ms. This comparison is shown in Figure 1 and has been described in our paper "Rotation of the Earth from Lunar Laser Ranging," to be published in the Proceedings of the International Astronomical Union (IAU) Colloquium No. 63 on High-Precision Earth Rotation and Earth-Moon Dynamics, held at Grasse, France, 22-27 May 1981 [Langley _et al_., 1982c].

B. Length of Day and Atmospheric Angular Momentum

In collaboration with R. D. Rosen and D. A. Salstein of ERT, Inc., we have compared changes in length-of-day (lod) derived from LLR estimates of Universal Time, with changes in lod inferred from variations in the angular momentum of the atmosphere. This comparison established the existence of a persistent fluctuation with period near 50 days which is common to both lod and atmospheric angular momentum and is present for at least the four-year span of the two data sets. This work is described in Langley _et al_. [1982b].

C. Preliminary Determination of the Orroral-McDonald Baseline Length

Since the arrival at M.I.T. in January 1981 of Dr. Peter J. Morgan of the Division of National Mapping (Natmap) of the Australian Department of National Resources and Development, we have carried out an analysis of the LLR observations made by Natmap's Orroral Lunar Ranging Station from 1978 through 1980. Normal-point residuals from many of the observations made before April 1980 using a 20 ns, multiple-mode laser pulse are discretely spaced, at multiples of 6 ns, and may have been corrupted by variations in pulse shape. Further evaluation is required before these observations can be used effectively in scientific analyses. Observations performed during the MERIT

Short Campaign using a 6 ns, single-mode pulse are apparently reliable. Using 27 single photoelectron events, obtained on 7 nights during this period, we have estimated the coordinates of Orroral, with respect to McDonald, with uncertainties of 1-2 m in cylindrical radius and longitude and 5-10 m in z-axis distance. Our results are described in Morgan and King [1982].

The analysis of lunar laser ranging observations carried out under this contract represents a continuation of work performed under a previous contract (F19628-79-C-0064) with AFGL. Through an oversight on our part, the acknowledgement of AFGL support in our papers submitted to the Journal of Geophysical Research and Nature included only the previous contract number. Our LLR analysis has also been sponsored in part by the National Aeronautics and Space Adminstration under Contract NAS5-25833, under the Lageos Satellite Program.

II. PERFORMANCE AND ANALYSIS OF VLBI OBSERVATIONS

A. Description of Observations

The new Mark III VLBI system was used by our group in four sessions to make observations at various sets of European and U.S. sites. These observations are described in Table 1 with the locations of the antennas shown in Figure 2.

In November 1979, mainly X-band ($\sim$8.4 GHz) observations were made. (Because this was the first field trial of the newly-constructed system, prudence dictated the use of only one frequency band.) For the 25th of November, observations were scheduled so as to optimize estimates of the baseline lengths from the east coast of the United States to the European sites; for the 26th of November, the schedule was designed to optimize estimates of the baselines between the east and the west coasts of the United States.

In July 1980, observations were obtained at both X-band ($\sim$8.4 GHz) and S-band ($\sim$2.3 GHz). By observing at these two widely separated frequencies, we were able to determine, and to correct for, the frequency dependent ionospheric propagation delay. (In Section II.C., we discuss tests of the precision of this correction.) The schedule was here designed as a compromise between ones that would optimize either of the two types of baselines discussed above. Since all sources had to be observable simultaneously from both Europe and the west coast of the United States, there were no low elevation observations obtained at the Haystack Observatory on the east coast of the

United States. Also, the ~8,000 km separation of the west coast of the United States from Europe limited the amount of time available for observing any given low-declination source. These geometrical constraints in the "compromise" schedule increased the uncertainties of the baseline determinations.

The September and October 1980 observations were made as part of the MERIT Short Campaign. The same schedule of observations was used each day with the epoch of corresponding observations on successive days displaced by approximately 4 minutes to account for the rate difference between universal and sidereal time. The schedule involved "subnetting" (different subsets of telescopes sometimes observing different sources at a given time) in an attempt to overcome the lack of sufficient mutual visibility of low declination radio sources from the west coast of the United States and from Europe.

Earlier Mark I experiments involving radio telescopes in the United States and Europe were described in Herring _et al_. [1981].

B. Preliminary Determinations of Baseline Lengths

The basic observations were primarily of the interferometric group delay [Shapiro, 1976], made simultaneously at X-band (~8.4 GHz) and S-band (~2.3 GHz) for the last three sessions of observations, and at X-band alone for the first session and the Mark I experiments. A multichannel bandwidth synthesis technique [Whitney _et al_., 1976] was used throughout. For the Mark III observations each single channel had a bandwidth of 4 MHz comprised of the upper and lower sidebands extending 2 MHz from a local-oscillator reference frequency. The synthesized bandwidths spanned by the multiple channels were 300 MHz at 8.4 GHz and 75 MHz at 2.3 GHz. Herring et al. [1981] give a detailed description of the corresponding Mark I observations.

The theoretical models and the coordinate system definitions used in the analysis of the observations are summarized in Herring et al. [1981]. The dual-band (S-X) observations enabled us to determine separately, and to account for, the delays introduced by the ionosphere. Surface weather data were used to estimate the delays due to the troposphere. For each day appropriate free parameters were included in the theoretical model to account for clock behavior and residual tropospheric path delays.

For all sessions of observations, including the earlier Mark I results, we have obtained estimates of the baseline lengths between the Onsala Space Observatory and stations in the United States. These estimated baseline lengths are given in Table 2. The weighted RMS scatter of these results is 3 cm which is twice the amount to be expected from random error. For comparison we have also given the Haystack-Owens Valley baseline length determinations.

The baseline lengths to Onsala which were obtained when no ionospheric delay calibration data were available are approximately 10 cm longer than the estimates obtained when the ionospheric delay calibration data were available (and used). It is not clear yet whether this difference is due to neglecting the ionospheric delay in the earlier experiments or due to an error in the ionospheric correction itself in the later experiments. In Section II.C. of this report we discuss the accuracy of the ionospheric correction as deduced from comparison of ionospheric delays calculated from group and phase delays. There is clearly a systematic difference between the corrections deduced from these two observable types; however, the magnitude of this difference would imply possible errors in the baseline length determinations of only 1 cm. The neglect of the ionospheric delay correction does not seem to be solely responsible for the difference between the earlier and later determinations of the baselines to Onsala because the corresponding baseline lengths from the U.S. sites to Effelsberg do not show a marked change when the ionospheric delay is accounted for (see below). We are therefore left with no plausible explanation for these differences at this time.

From the first three sessions of observations described in Table 1 we have obtained preliminary estimates of the baseline lengths between Effelsberg and the other participating antennas, as shown in Table 3. The weighted RMS scatter of the individual estimates about their weighted mean values is 2 to 3 cm for each of these baselines. The estimated standard deviations for the baselines from the Ft. Davis and Owens Valley sites to Effelsberg for the last two experiments are larger, a result of the constraints of the schedule which, as mentioned, was designed to optimize the estimates of different baselines. (Results from only one of the days of observations in July are presented because the remaining data are still being analyzed; in particular we are investigating the possibility of systematic biases having been caused by the lack of low elevation observations at the Haystack Observatory.)

In the fourth session of observations a transportable VLBI system was used at Chilbolton, England. Table 4 presents the baseline length estimates obtained by analyzing separately each of the seven days of these observations. The weighted RMS scatters vary between 2 and 9 cm, and, for each baseline, are approximately twice the scatter expected from random error.

All of these data are still being analyzed to try to determine why the scatter of the residuals is twofold greater than predicted from the statistics of the measurements.

C. Accuracy of the Correction for Ionospheric Effects

Six hours during the July 1980 experiment were devoted to alternate observations of just two radio sources, 3C 345 and NRAO 512. Because these sources are separated by only $0\overset{\circ}{.}5$ in the sky, the time interval between successive observations of either source was sufficiently short that the integer-cycle ambiguity of the fringe phase for one observation could be resolved by reference to the preceding or following observation. Using these data, we were thus able to compute the ionospheric contributions to the group delays using four combinations of observables: 1) the X-band and S-band group delays; 2) the X-band group and the X-band phase delays; 3) the S-band group and the S-band phase delays; and 4) the X-band and the S-band phase delays. Figure 3 shows the ionospheric delays for the two radio sources deduced from the X- and S-band phase delays for the Effelsberg-Onsala baseline. The large differences between the two curves near sunrise might be due to the separation of the sources on the sky. Figure 4 shows the differences between the ionospheric delays for the signals from 3C 345 deduced from the X- and S-band phase delays and from the other sets of observables, discussed above. Clearly, there are significant differences between the results from each of the methods used for calculating the ionospheric delay. There are several possible explanations for these differences, for example either differences in the contributions of source structure to the group and phase delays at X- and S-bands, or undetected instrumental problems, or some combination.

These results are encouraging despite the systematic differences, because they are all smaller than the X- and S-band phase delay ambiguities. This fact implies that for short baselines ($\lesssim$800 km), at least, we should be able to eliminate the phase-delay ambiguities by using the group-delay observations, without the need for spacing the observations closely in time. Thus, we could use unambiguous phase delays, freed from ionospheric effects to determine baselines. The resulting decrease in the random error of the delays ($\sim$40-fold) would allow us to discern clearly any remaining systematic errors in our observations.

The estimates of the ionospheric contributions to the delays for the long baseline, Haystack-Effelsberg, are shown in Figures 5 and 6. For this baseline, the ionospheric delays calculated from the X- and S-band phase delays obtained from observations of the two radio sources yield significantly different results [*Figure* 5(*a*)], although the delays calculated from the X-band group and the X-band phase delays do not seem systematically different (despite the random error contribution to the NRAO 512 results being substantially higher in this case). It is possible that the differences between the ionospheric delays deduced from the phase-delay data for the two sources are due to the brightness structure of 3C 345. We are currently attempting to determine this structure so as to correct the observations appropriately and thereby to test this hypothesis.

D. Estimation of Solid-Earth Tide Parameters

Using the data from the MERIT session of observations, we also estimated the solid earth tide parameters. The results of this analysis were presented at the Ninth International Symposium on Earth Tides in New York and will be published in the proceedings of that symposium [Herring et al., 1982].

Our VLBI experiments and data analysis have also been supported in part by the National Science Foundation, Grants EAR-7920253, 8106036-PHY, and AST-8022229, the National Aeronautics and Space Administration, Contract NGR22-009-839, and the U.S. Geological Survey, Contract 14-08-0001-18388.

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Table 1. Summary of Experiments

Dates	Antennas[1]	Duration (days)	Frequencies[2]
25-26 Nov 1979	HA, NR, OV, EF, ON	1.5	X only
26-27 July 1980	HA, HR, OV, EF, ON	2.0	X and S
26-27 Sept 1980	HA, HR, OV, EF, ON	2.0	X and S
28 Sept - 1 Oct 1980	HA, HR, OV, ON	5.0	X and S
16-22 Oct 1980	HA, HR, OV, ON, CH	7.0	X and S

[1] Codes: HA - Haystack Observatory, Massachusetts
NR - National Radio Astronomy Observatory, West Virginia
HR - Harvard Radio Astronomy Station, Texas
OV - Owens Valley Radio Observatory, California
EF - Effelsberg Radio Telescope, F.R. Germany
ON - Onsala Space Observatory, Sweden
CH - Chilbolton Observatory, England

[2] Frequencies used during observations: X-band ~8.4 GHz and S-band ~2.3 GHz.

Table 2. Preliminary Estimates of Baseline Lengths from Onsala to Other Antennas

Date	Baseline Lengths[1,2] HA-ON (m)	NR-ON (m)	HR-ON (m)	OV-ON (m)	[illegible]A-OV (m)
9/21/77 & 2/24/78	5,599,174.62±0.06	6,319,317.75±0.07	7,940,732.	7,914,131.29±0.08	3,928,881.72±0.02
5/17/78	4.66±0.03	7.75±0.03		1.19±0.04	1.67±0.01
11/25/79	4.62±0.02	7.73±0.02		1.20±0.03	1.64±0.01
7/26/80	4.48±0.02		2.30±0.02	1.06±0.03	1.64±0.01
9/26/80	4.56±0.02		2.37±0.07	1.08±0.04	1.66±0.02
9/27/80	4.52±0.03		2.22±0.07	1.10±0.05	1.70±0.04
9/29/80	4.56±0.03		2.32±0.07	1.10±0.04	1.67±0.02
9/30/80	4.55±0.02		2.21±0.07	1.06±0.04	1.63±0.01
9/31/80	4.55±0.06		2.48±0.07	1.18±0.05	1.65±0.01
10/1/80	4.55±0.03		2.20±0.05	0.98±0.03	1.62±0.01
10/16/80	4.58±0.01		2.28±0.05	1.11±0.03	1.66±0.01
10/17/80	4.55±0.02		2.38±0.05	1.16±0.03	1.66±0.01
10/18/80	4.52±0.03		2.41±0.06	1.16±0.05	1.62±0.02
10/19/80	4.51±0.01		2.16±0.04	1.09±0.06	1.66±0.03
10/20/80	4.53±0.01		2.28±0.04	1.08±0.04	1.64±0.01
10/21/80	4.54±0.01		2.39±0.03	1.12±0.02	1.65±0.01
10/22/80	4.54±0.01		2.33±0.03	1.11±0.02	1.66±0.01
Weighted Mean±	4.55±0.03	7.74±0.010	2.31±0.07	1.11±0.06	1.65±0.02
Weighted RMS[3]					

[1] The reference point for each telescope is the intersection of the azimuth and elevation axes, except for NR and HR where the reference is the point on the polar axis closest to the (non-intersecting) equatorial axis. (See Table 1 for the antenna code.)

[2] The speed of light used to convert light seconds to meters was 299,792,458 ms^{-1}.

[3] Weighted-root-mean-square scatter of the results about their weighted mean values.

Table 3. Preliminary Estimates of Baseline Lengths from Effelsberg to Other Antennas

Date	Baseline Lengths[1] HA-EF (m)	NR-EF (m)	HR-EF (m)	OV-EF (m)	ON-EF (m)
25-26 Nov 1979	5,591,903.61±0.01	6,334,648.63±0.02	--	8,203,742.64±0.02	832,210.46±0.01
26 July 1980	03.57±0.02	--	8,084,184.97±0.02	42.60±0.03	10.53±0.01
26 Sept 1980	03.59±0.02	--	84.96±0.07	42.54±0.05	10.52±0.01
27 Sept 1980	03.58±0.03	--	84.86±0.07	42.62±0.05	10.53±0.01
Weighted Mean± Weighted RMS[2]	5,591,903.60±0.02	6,334,648.63	8,084,184.96±0.03	8,203,742.62±0.03	832,210.51±0.03

1 See footnotes 1 and 2, Table 2.

2 See footnote 3, Table 2.

Table 4. Preliminary Estimates of Baseline Lengths from Chilbolton to Other Antennas

Date	Baseline Lengths[1]			
Oct 1981	HA-CH (m)	HR-CH (m)	OV-CH (m)	ON-CH (m)
16	5,072,314.51±0.02	7,663,737.37±0.06	7,846,991.32±0.04	1,109,864.33±0.01
17	14.49±0.02	37.49±0.05	91.39±0.04	64.38±0.01
18	14.50±0.02	37.62±0.05	91.51±0.04	--.--[3]
19	14.50±0.01	37.33±0.04	91.38±0.06	64.34±0.01
20	14.54±0.02	37.48±0.04	91.41±0.04	64.34±0.01
21	14.51±0.01	37.45±0.03	91.34±0.02	64.35±0.01
22	14.53±0.01	37.56±0.03	91.41±0.02	64.35±0.01
Weighted Mean± Weighted RMS[2]	5,072,314.51±0.02	7,663,737.48±0.09	7,846,991.39±0.05	1,109,864.35±0.02

[1] See Footnotes 1 and 2, Table 2.

[2] See Footnote 3, Table 2.

[3] Due to very high winds at the Onsala Space Observatory on this day, there were insufficient data to allow a reliable estimate of this baseline length.

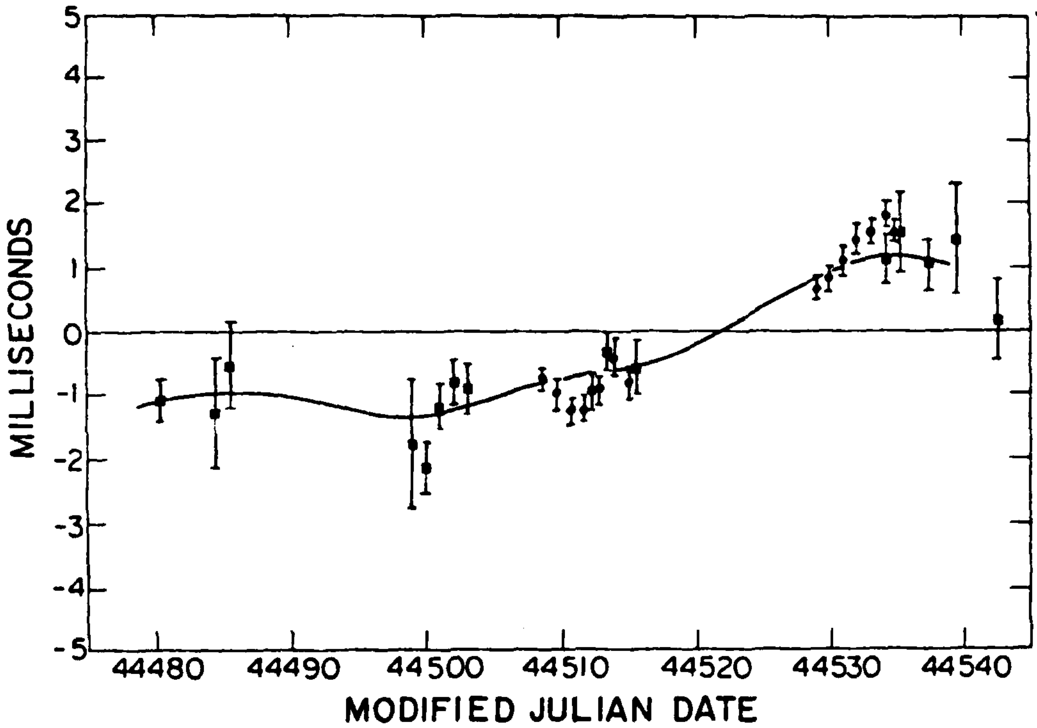
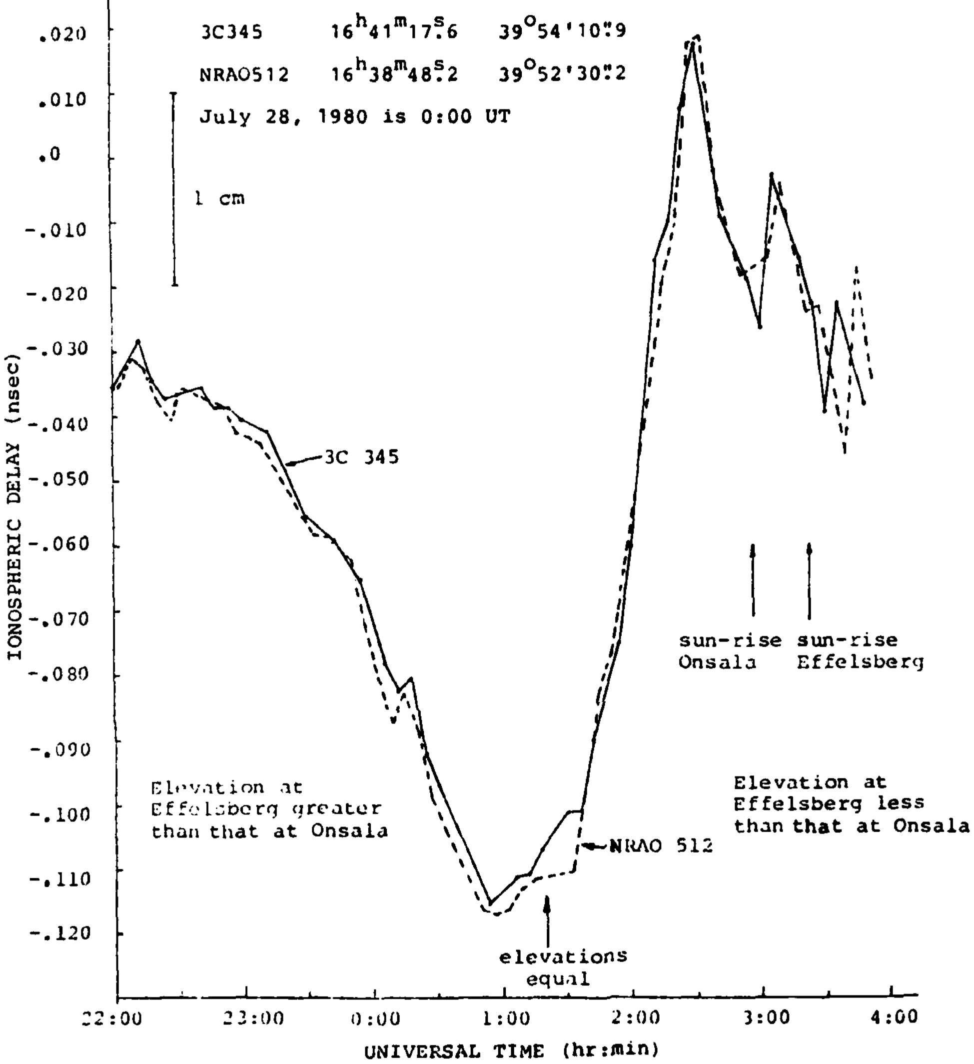


Figure 1. UTO at McDonald Observatory from LLR and VLBI observations minus UTO derived from the smoothed Circular D pole-position and UT1 values published by the BIH (Vondrák smoothing parameter $\varepsilon = 10^{-7}$) for the period covered by the MERIT Short Campaign. Fortnightly and monthly tidal terms have been removed from both the LLR and VLBI values . LLR daily values: , VLBI daily values: . The curve was obtained from a smoothing of the LLR daily values. Modified Julian Date 44480 corresponds to 29 August 1980.

Figure 2. ANTENNA LOCATIONS (see Table 1 for Antenna Code)

Figure 3. Relative Ionospheric Delay for Signals received at Effelsberg and Onsala, Calculated from X-Band and S-Band Phase Delay Measurements. (The source coordinates are referred to the mean equinox and equator of 1950.0.)



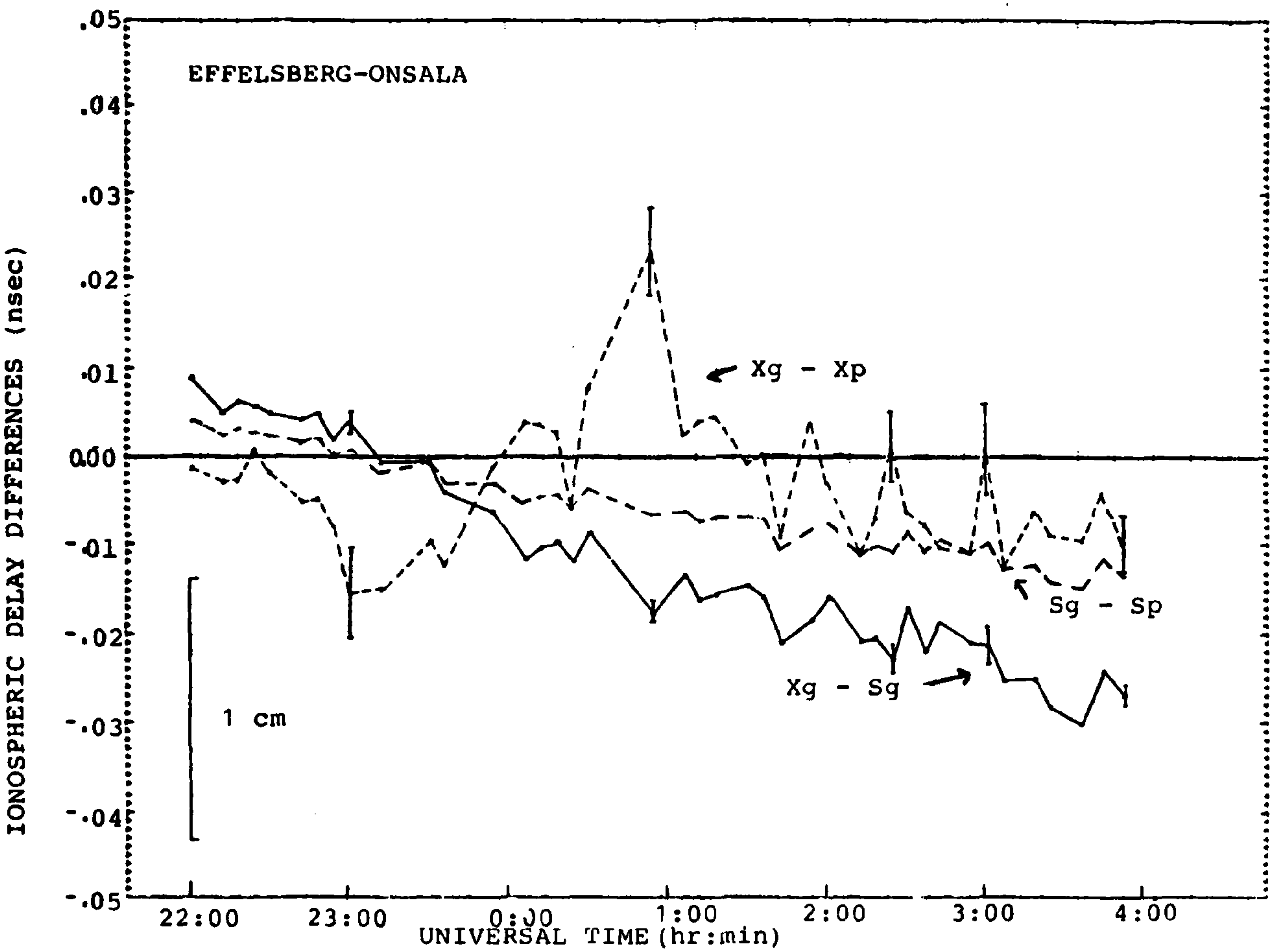


Figure 4. Differences between ionospheric delays for signals received at Onsala and Effelsberg from 3C 345 calculated from X-Band and S-Band phase delays and from other observables (see text). Subscripts g and p denote group and phase delays, respectively.

Figure 5a. Relative Ionospheric Delay for Observations from Haystack and Effelsberg, calculated from X-Band and S-Band Phase Delays.

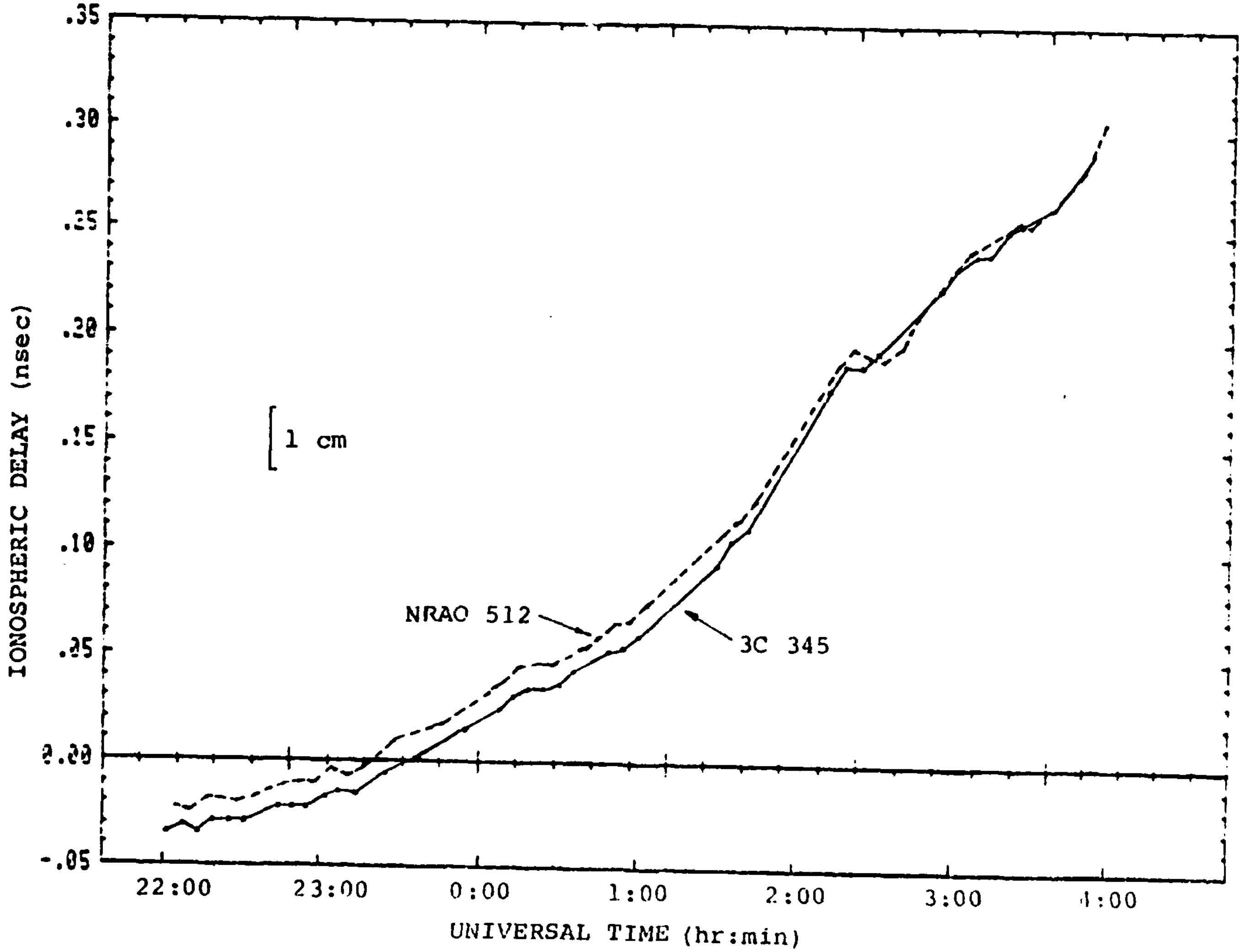
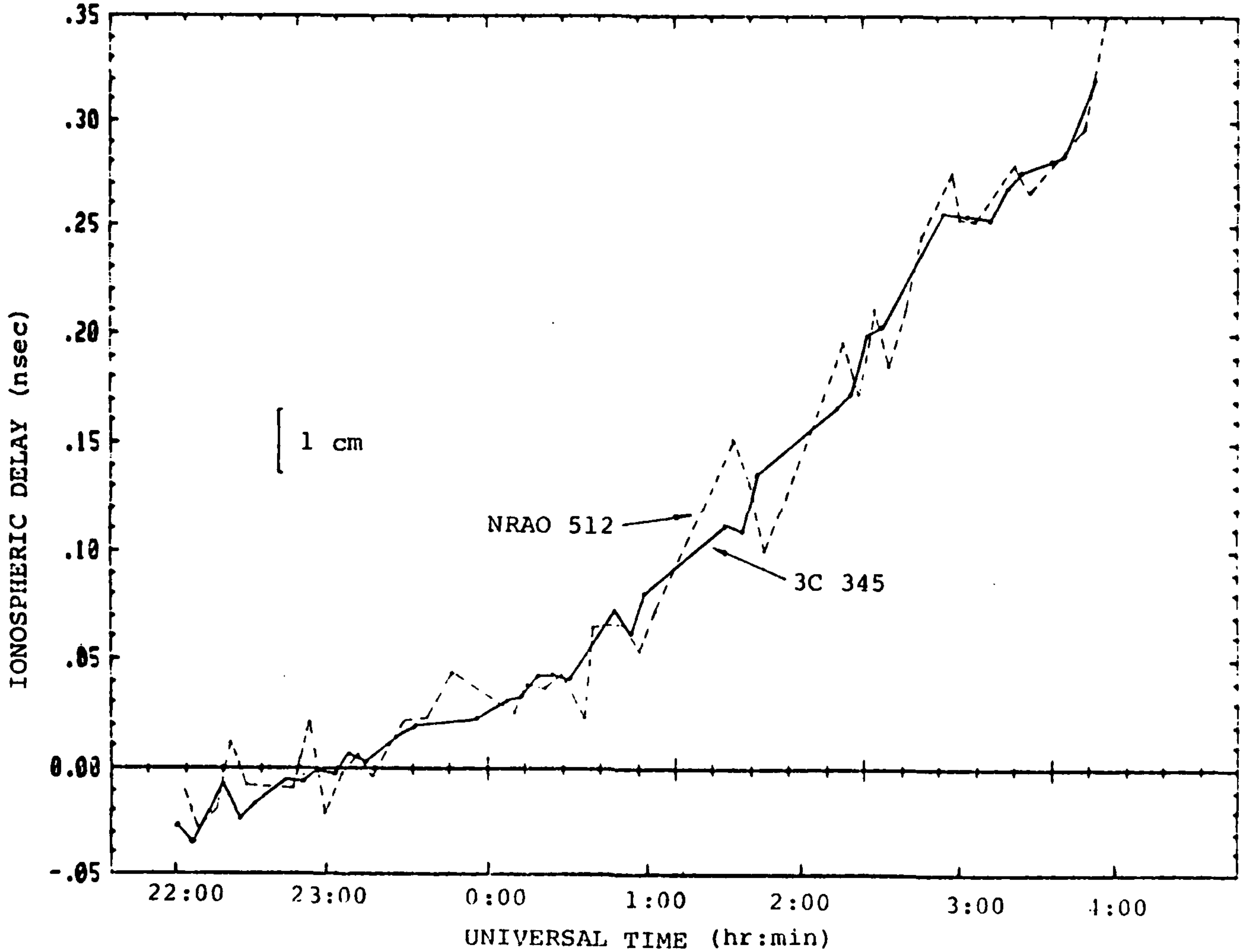


Figure 5b. Relative Ionospheric Delay for Observations from Haystack and Effelsberg, calculated from X-Band Group and Phase Delays.



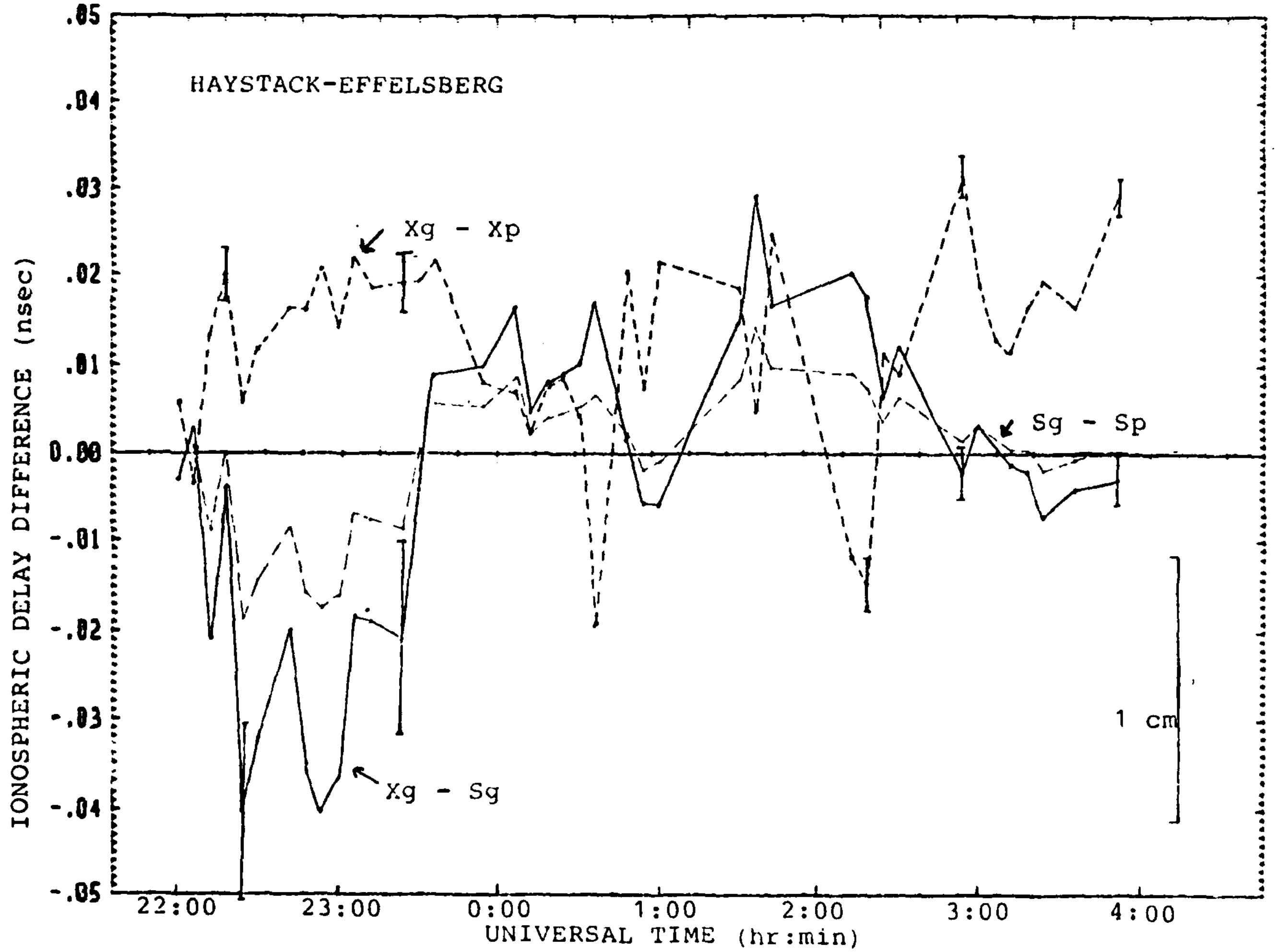


Figure 6. Same as Figure4,except for observations from Haystack and Effelsberg.

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